



Original Article

## Environmental Determinants of Fecal Microplastic Abundance: A Cross-Sectional Study in the Musi River Basin, Indonesia

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### ABSTRACT

**Background:** Microplastics have been detected across multiple environmental compartments and can enter the human body through food and drinking water, representing an emerging concern in environmental toxicology related to chronic human exposure.

**Methods:** A cross-sectional study was conducted among residents of the Musi River watershed, Indonesia, involving samples of refilled drinking water, tea products, and human feces. Microplastics were identified using digital microscopy and classified according to GESAMP guidelines. Associations between environmental exposure factors and fecal microplastic abundance were analyzed using correlation analysis and multiple linear regression.

**Results:** Microplastics were detected in all analyzed matrices. Fecal microplastic abundance was significantly associated with duration of residence ( $r = 0.241$ ,  $p = 0.041$ ), consumption of refilled drinking water ( $r = 0.284$ ,  $p = 0.037$ ), and teabag consumption ( $r = 0.312$ ,  $p = 0.021$ ). Teabag consumption showed the strongest association; however, documented consumption patterns indicated that teabags were routinely prepared using refilled drinking water. In multivariate analysis, all three factors were independent predictors, explaining 31.2% of the variance ( $R^2 = 0.312$ ;  $p < 0.05$ ).

**Conclusion:** Microplastics present in refilled drinking water and teabags represent an additional route of human exposure that should be considered in strategies to improve drinking water quality and reduce environmental health risks.



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## INTRODUCTION

Microplastics are increasingly recognized as emerging environmental contaminants with the potential to affect human health through mechanisms such as inflammation, oxidative stress, and disruption of gastrointestinal integrity and endocrine function (Kadac-Czapska et al., 2022; Vethaak & Legler, 2021; Xu et al., 2022). Chronic ingestion or inhalation of micro- and nanoplastics has become a growing public health concern, as these particles have been detected in various human biological matrices, including feces, blood, and lung tissue (Hart et al., 2023; Leslie et al., 2022; Schwabl et al., 2019). These findings indicate that humans are not merely passive endpoints of environmental plastic contamination, but active participants within complex exposure pathways.

Despite increasing documentation of microplastics in human tissues, understanding remains limited regarding how specific environmental exposure pathways and everyday behavioral patterns cumulatively influence internal microplastic burden at the community level. This gap is particularly evident in urban river basin settings, where routine drinking water and beverage consumption behaviors intersect with environmental contamination sources (Thin et al., 2025; Vdovchenko & Resmini, 2024).

Previous studies have identified food and drinking water as major sources of human microplastic exposure (Campanale et al., 2020; Li et al., 2018). Microplastics have been detected in both refilled and bottled drinking water, often attributed to inadequate filtration, storage, and distribution processes (Eerkes-Medrano et al., 2018). Similarly, teabags composed of nylon and polyethylene terephthalate (PET) have been shown to release substantial quantities of microplastic particles into hot water during brewing (Hernandez et al., 2019; Peng et al., 2023). Consequently, habitual consumption of refilled drinking water and teabags represents a potentially important pathway for chronic human microplastic exposure.

However, recent reviews emphasize that evaluating exposure sources in isolation fails to capture the complex interplay between habitual consumption practices and environmental contamination. This underscores the need for assessments that consider behavioral exposure pathways within real-world contexts (Tang, 2025).

In addition to consumption patterns, demographic characteristics including age, educational level, occupation, and duration of residence may further influence exposure magnitude (Lusher et al., 2017; Mason et al., 2020). For example, adults of productive age often rely on refilled drinking water for convenience, whereas older individuals may consume teabags more frequently as part of established daily routines. Such behavioral differences may contribute to observed variations in fecal microplastic abundance across population groups.

Emerging evidence from systematic reviews also suggests that microplastic exposure may alter the human gut microbiome and associated metabolic pathways, indicating that cumulative dietary and water-based exposure may have biological implications beyond the mere presence of particles in human tissues (Jabri et al., 2024). These findings further highlight the importance of integrating both environmental and behavioral factors in microplastic exposure assessment.

Although numerous studies have reported the presence of microplastics in human feces, relatively few have examined how demographic characteristics and everyday consumption behaviors particularly refilled drinking water and teabag consumption are associated with microplastic abundance, especially in the Indonesian context. By adopting an observational framework focused on environmentally mediated exposure pathways rather than clinical outcomes, this study addresses a critical gap in environmental toxicology regarding how daily behaviors and environmental conditions jointly contribute to microplastic accumulation in human biological matrices (Vdovchenko & Resmini, 2024).

Therefore, this study aims to analyze the associations between demographic characteristics and the consumption patterns of refilled drinking water and teabags with fecal microplastic abundance among residents of the Musi River Basin (DAS Musi), Palembang. The findings are intended to provide a scientific basis for improving drinking water quality monitoring and promoting safer consumption practices to reduce potential human exposure to microplastics.

## **METHODS**

This study employed an observational cross-sectional design conducted between February and July 2025 in the Musi River Basin (MRB), Palembang City, Indonesia. The study population comprised residents living in the MRB area, refilled drinking water from active water depots, and commercially available teabag and loose-leaf tea products. Samples included refilled drinking water from 12 depots,

16 teabag brands, 15 loose-leaf tea brands, and fecal samples from 97 respondents selected using simple random sampling.

Microplastic identification in all samples was performed using digital microscopy following standardized microscopic observation protocols. Sample preparation was conducted using distilled water (aquadest) in sterilized glass containers to prevent cross-contamination. Microplastics were classified by morphology (fiber, fragment, and film), size ( $\mu\text{m}$ ), and color in accordance with GESAMP guidelines (GESAMP, 2021).

All solvents used during sample preparation consisted exclusively of analytical-grade aquadest and were stored in pre-cleaned glass bottles. Plastic laboratory ware was strictly avoided throughout all stages of sample processing to minimize the risk of secondary contamination.

For fecal samples, organic matter was removed prior to microscopic observation using chemical reagents following standardized digestion procedures commonly applied in microplastic analysis. This procedure effectively destructed organic fecal matrices while maintaining the integrity of plastic particles, thereby enhancing microscopic detection accuracy and minimizing false-positive identification.

Sociodemographic and behavioral data including age, sex, education, body weight, duration of residence, and consumption patterns of refilled drinking water and teabags were collected through structured interviews using a validated questionnaire. Questionnaire development, reliability, and validity followed established methodological principles (Boateng et al., 2018) and were adapted for environmental exposure assessment. Internal consistency was evaluated during a pilot phase, and only items demonstrating acceptable reliability were retained. The instrument was designed to capture habitual exposure patterns rather than short-term intake.

Descriptive statistics were used to summarize microplastic distribution and morphological characteristics across sample types. Pearson's correlation analysis was applied to examine associations between exposure variables and fecal microplastic abundance. Multiple linear regression analysis was subsequently conducted to identify independent predictors while controlling for demographic covariates. Regression assumptions including normality, linearity, and multicollinearity were verified prior to interpretation, consistent with recommended analytical practices (Schober et al., 2018).

Multiple linear regression was selected because fecal microplastic abundance was a continuous and normally distributed outcome variable. Logistic regression was not applied due to the absence of categorical outcomes. Model performance was assessed using the coefficient of determination ( $R^2$ ). Statistical analyses were performed using appropriate statistical software, with significance set at (Mukaka, 2012).

Procedural blank controls using aquadest were included to monitor laboratory contamination during sample processing and microscopic analysis. No microplastic particles were detected in blank samples, indicating negligible background contamination. The analytical focus was limited to particles  $\geq 50 \mu\text{m}$ , consistent with the reliable detection threshold of digital microscopy and common practice in preliminary human exposure studies.

Ethical approval was obtained from the Health Research Ethics Committee of Politeknik Kesehatan Kemenkes Palembang (Approval No. 0105/KEPK/Adm2/II/2025).

## RESULTS

A total of 97 respondents were included in the study, representing residents from nine urban subdistricts within the Musi River Basin (MRB), Palembang City: Bukit Kecil, Ilir Barat II, Kalidoni, Ilir Timur I–III, Kertapati, Seberang Ulu I–II, Plaju, and Gandus.

Demographic characteristics indicated that 71.1% of respondents were female and 28.9% were male. Participant ages ranged from 20 to 79 years, with a mean age of  $47.6 \pm 13.5$  years. Educational attainment varied, with 37.1% completing elementary school, 28.9% junior high school, 24.7%

senior high school, and 9.3% attaining tertiary education (Diploma or Bachelor's degree). The mean body weight was  $58.3 \pm 10.7$  kg. Respondents had resided in the MRB area for an average of  $33.5 \pm 15.8$  years, reflecting prolonged environmental exposure.

Consumption behavior analysis showed that 89.7% of respondents consumed refilled drinking water on a daily basis. Teabag consumption was also prevalent, with 78.4% reporting daily intake and 12.4% consuming teabags two or more times per day. These patterns indicate sustained and routine exposure pathways for potential microplastic ingestion through drinking water and beverage consumption. The abundance of microplastics per teabag sample is presented in Table 1.

**Table 1. Descriptive statistics of microplastic abundance in teabag samples**

Parameter	Min	Max	Median	95% CI	Dominant Form	Secondary forms	Dominant Color
Microplastic abundance (particles/g)	10	120	30	27.22 – 54.03	Fiber	Fragment, Film	Black

As shown in Table 1, microplastic abundance in teabag samples ranged from 10 to 120 particles/L, with a mean of  $40.0 \pm 25.16$  particles/L (95% CI: 27.22–54.03). Fiber-type microplastics predominated, followed by fragments and films, reflecting polymer release from teabag materials during brewing. The dominant color black in terms of color. Although concentrations were lower than those in refilled drinking water, teabags represent a recurrent secondary exposure source, particularly when brewed using refilled water.

The abundance and morphology of microplastics in refilled drinking water samples are shown in Table 2.

**Table 2. Descriptive statistics of microplastic abundance in water refilled depots samples**

Parameter	Min	Max	Mean $\pm$ SD	95% CI	Dominant Form	Secondary Forms	Dominant Color
Microplastic abundance (particles/g)	300	790	$620 \pm 160$	508.20 – 711.80	Fragment	Fiber, Film	Black; Brown

As shown in Table 2, microplastic concentrations in refilled drinking water ranged from 300 to 790 particles/L, with a mean of  $620 \pm 160$  particles/L (95% CI: 508.20–711.80). Fragment-type particles predominated, followed by fibers and films, with black and brown colors most frequently observed. These findings indicate widespread microplastic contamination in refilled drinking water in the Musi River Basin, supporting its role as a continuous environmental exposure pathway.

The descriptive statistics of microplastic abundance identified in fecal samples are presented in Table 3.

**Table 3. Descriptive statistics of microplastic abundance in fecal samples**

Parameter	Minimum	Maximum	Mean $\pm$ SD	95% CI	Dominant Form	Dominant Color
Microplastic abundance (particles/g)	6.1	36.0	$15.8 \pm 7.2$	13.1 – 18.5	Fragment	Black, Transparent

As presented in Table 3, microplastic abundance in fecal samples ranged from 6.1 to 36.0 particles per gram, with a mean concentration of  $15.8 \pm 7.2$  particles/g. The 95% confidence interval (13.1–18.5 particles/g) indicates moderate interindividual variability among respondents. Fragment-type microplastics were the most frequently detected, and black and transparent particles

predominated in terms of color. These results suggest continuous exposure to microplastics among residents of the Musi River Basin, plausibly linked to routine consumption of refilled drinking water and teabag-based beverages.

The relationship between microplastic abundance in fecal samples and potential influencing factors, including demographic characteristics and consumption patterns, was analyzed using Pearson’s and Spearman’s correlation tests. The results are summarized in Table 2.

**Table 4. Correlation between fecal microplastic abundance, demographic characteristics, and consumption patterns**

Variables	r	r <sub>s</sub>	R <sup>2</sup>	Regression Equation	p-value
Age (years)	0.176		0.031	$Y = 8.14 + 0.12X$	0.089
Education level		-0.154			0.127
Length of residence (years)	0.241		0.058	$Y = 9.72 + 0.18X$	0.041*
Body weight (kg)	-0.103		0.011	$Y = 14.23 - 0.09X$	0.351
Refilled drinking water	0.284		0.081	$Y = 7.65 + 0.21X$	0.037*
Teabag consumption	0.312		0.097	$Y = 6.90 + 0.25X$	0.021*

As shown in Table 4, correlation analyses were conducted to examine the associations between fecal microplastic abundance and selected demographic characteristics and consumption-related environmental exposure factors.

Among demographic variables, length of residence in the Musi River Basin was significantly and positively correlated with fecal microplastic abundance ( $r = 0.241$ ,  $p = 0.041$ ;  $R^2 = 0.058$ ). The corresponding linear regression model ( $Y = 9.72 + 0.18X$ ) indicates that each additional year of residence was associated with an estimated increase of 0.18 microplastic particles per gram of feces, suggesting a cumulative effect of prolonged environmental exposure.

In contrast, age ( $r = 0.176$ ,  $p = 0.089$ ) and body weight ( $r = -0.103$ ,  $p = 0.351$ ) were not significantly associated with fecal microplastic abundance. Education level, assessed using Spearman’s rank correlation, also showed no significant relationship ( $r_s = -0.154$ ,  $p = 0.127$ ), indicating that formal educational attainment was not associated with variation in microplastic burden.

Regarding consumption-related behaviors, refilled drinking water consumption demonstrated a significant positive correlation with fecal microplastic levels ( $r = 0.284$ ,  $p = 0.037$ ;  $R^2 = 0.081$ ). The regression equation ( $Y = 7.65 + 0.21X$ ) suggests that increased reliance on refilled drinking water was associated with higher microplastic abundance in fecal samples. Teabag consumption exhibited the strongest association among all variables examined ( $r = 0.312$ ,  $p = 0.021$ ;  $R^2 = 0.097$ ), with the corresponding regression model ( $Y = 6.90 + 0.25X$ ) indicating a measurable contribution of this dietary habit to microplastic ingestion.

Overall, these findings indicate that duration of environmental exposure and specific consumption behaviors particularly refilled drinking water and teabag use are more strongly associated with fecal microplastic abundance than intrinsic demographic characteristics. Nevertheless, the relatively low  $R^2$  values suggest that microplastic exposure is influenced by multiple interacting pathways beyond the factors assessed in this study.

A multivariate linear regression analysis was performed to assess the combined effects of length of residence, refilled drinking water consumption, and teabag consumption on fecal microplastic abundance. All three variables remained significant independent predictors of increased microplastic concentrations.

**Table 5. Multiple linear regression analysis of factors associated with fecal microplastic abundance**

Variables	B (Unstandardized coefficient)	Standardized Beta ( $\beta$ )	p-value	Interpretation
Length of residence (years)	0.186	0.214	0.031*	Significant predictor
Refilled drinking water	0.241	0.273	0.015*	Significant predictor
Teabag consumption	0.278	0.298	0.009*	Strongest predictor

Model summary:  $R^2 = 0.312$ ; Adjusted  $R^2 = 0.287$ ;  $F=21.3$ ;  $p < 0.05$

As shown in Table 5, length of residence was significantly and positively associated with fecal microplastic abundance ( $B = 0.186$ ,  $\beta = 0.214$ ,  $p = 0.031$ ), indicating that longer residence in the Musi River Basin was linked to greater microplastic accumulation, consistent with cumulative environmental exposure over time.

Refilled drinking water consumption also emerged as a significant predictor ( $B = 0.241$ ,  $\beta = 0.273$ ,  $p = 0.015$ ), with higher consumption frequencies associated with increased fecal microplastic levels, supporting its role as an important environmental exposure pathway.

Teabag consumption showed the strongest association with fecal microplastic abundance ( $B = 0.278$ ,  $\beta = 0.298$ ,  $p = 0.009$ ), reflecting repeated exposure related to polymer particle release during brewing, particularly in the context of routine use of refilled drinking water.

The overall regression model demonstrated moderate explanatory power ( $R^2 = 0.312$ ; adjusted  $R^2 = 0.287$ ) and was statistically significant ( $F = 21.3$ ,  $p < 0.05$ ), indicating that these environmental and consumption-related factors collectively explained 31.2% of the variability in fecal microplastic abundance among Musi River Basin residents.

Collectively, these findings suggest that long-term residence and habitual consumption behaviors act synergistically as environmentally mediated determinants of human microplastic burden in this river basin population.

## DISCUSSION

### Microplastic Abundance in Refilled Water, Teabags, and Human Feces

This study provides comprehensive evidence of human exposure to microplastics through two routine consumption pathways refilled drinking water and teabags. Microplastics were detected in all analyzed matrices, confirming continuous exposure among residents of the Musi River Basin, Palembang.

Refilled drinking water contained 300–790 particles  $L^{-1}$  (mean =  $620 \pm 160$ ), with black and transparent fragments accounting for 59.4% of detected particles. These morphological characteristics are indicative of secondary microplastics, likely originating from the degradation of polyethylene and polypropylene components used in filtration membranes, dispenser hoses, and storage tanks (Eerkes-Medrano et al., 2018; Novotna et al., 2019). The substantial variability observed across water depots suggests inconsistencies in filtration performance and hygiene practices during production and distribution. Recent studies on polymer degradation kinetics further demonstrate that repeated mechanical stress, hydraulic pressure, and material aging within drinking water systems preferentially generate irregular fragment-type microplastics rather than fibers, particularly from polyethylene- and polypropylene-based materials (Suyamud et al., 2024; Wang et al., 2023).

In contrast, teabag infusions contained 10–120 particles  $L^{-1}$  (median = 30 particles  $L^{-1}$ ), with pronounced inter-product variability. Microplastics associated with teabags were predominantly fibers, consistent with the release of thermoplastic polymer threads used in sealing and packaging materials (Hernandez et al., 2019; Yousefi et al., 2024). Although particle concentrations per serving were lower than those observed in drinking water, habitual tea consumption represents a relevant behavioral exposure pathway. Importantly, real-world exposure from teabags occurs within a

combined exposure context, as tea preparation in this population almost exclusively relies on refilled drinking water. Accordingly, teabags function as an exposure-modifying behavior rather than an independent dominant source, reinforcing ingestion frequency rather than contributing substantially higher particle loads (Tang, 2025).

Fecal microplastic abundance ranged from 6.1 to 36.0 particles  $g^{-1}$  (mean =  $15.8 \pm 7.6$ ), with fragments dominating (42%), followed by films (33%) and fibers (25%). The morphological similarity between fragment-type microplastics detected in feces and those identified in refilled drinking water supports the inference that refilled water represents the primary exposure vector. The predominance of fragments over fibers further suggests ingestion of environmentally derived secondary microplastics rather than direct transfer from teabag materials.

Fragment-dominated microplastic profiles similar to those observed in this study have been reported in recent human biomonitoring studies involving feces, blood, placenta, and gallstones, indicating that secondary microplastics originating from drinking water systems constitute a consistent internal exposure pattern across multiple biological matrices (Leslie et al., 2022; Ragusa et al., 2021; Vdovchenko & Resmini, 2024).

### **Correlation between Demographic and Consumption Factors with Fecal Microplastics**

Correlation analyses were conducted to assess the relationships between fecal microplastic abundance and selected demographic characteristics, as well as consumption-based environmental exposure factors (Table 4). Among demographic variables, length of residence showed a significant positive correlation with fecal microplastic abundance ( $r = 0.241$ ,  $p = 0.041$ ;  $R^2 = 0.058$ ). The corresponding linear regression model ( $Y = 9.72 + 0.18X$ ) indicates that each additional year of residence in the Musi River Basin was associated with an estimated increase of 0.18 microplastic particles per gram of feces. Although the proportion of explained variance was limited, this finding is consistent with the concept of cumulative environmental exposure associated with prolonged interaction with local water systems, as described in previous microplastic exposure studies (Q. Zhang et al., 2020). Given the cross-sectional design, this association should be interpreted as exposure-related rather than as evidence of biological accumulation.

In contrast, other demographic characteristics were not significantly associated with fecal microplastic abundance. Neither age ( $r = 0.176$ ,  $p = 0.089$ ) nor body weight ( $r = -0.103$ ,  $p = 0.351$ ) showed significant correlations, suggesting that intrinsic physiological factors exerted less influence than environmentally mediated exposure pathways. Education level, assessed using Spearman's rank correlation, was also not significantly associated with microplastic burden ( $r_s = -0.154$ ,  $p = 0.127$ ), indicating that formal educational attainment did not differentiate exposure levels within this population.

Among consumption-related behaviors, refilled drinking water consumption demonstrated a significant positive correlation with fecal microplastic abundance ( $r = 0.284$ ,  $p = 0.037$ ;  $R^2 = 0.081$ ). The regression equation ( $Y = 7.65 + 0.21X$ ) suggests that increased reliance on refilled drinking water was associated with higher fecal microplastic counts. Although the explanatory power of this association was modest, similar patterns have been reported in drinking water studies documenting widespread microplastic contamination across diverse water sources and distribution systems (Praveena et al., 2021). These findings suggest that refilled drinking water functions as a consistent exposure medium rather than a singular determinant of microplastic intake.

Teabag consumption exhibited the strongest correlation among all variables examined ( $r = 0.312$ ,  $p = 0.021$ ;  $R^2 = 0.097$ ). However, the relatively low coefficient of determination indicates that teabag consumption alone does not dominate microplastic exposure. Instead, it likely acts as a reinforcing behavioral factor within a broader exposure framework. This interpretation is supported by evidence showing that teabags, particularly those composed of polypropylene or nylon, can release substantial quantities of micro- and Nano plastics during brewing, thereby increasing ingestion frequency even when the particle mass contribution per serving is variable (Kadac-Czapska et al.,

2022). Importantly, correlation strength should not be equated with proportional contribution to total microplastic intake.

Morphological comparisons further contextualize these associations. Fragment-type microplastics, predominantly black and transparent, were dominant in both refilled drinking water and fecal samples, whereas microplastics released from teabags are more commonly fibrous. This morphological divergence supports the inference that refilled drinking water represents the primary source of fragment-type microplastics detected in feces, while teabag consumption likely increases exposure frequency rather than contributing the largest particle load. Experimental studies indicate that repeated exposure through hot beverages may enhance gastrointestinal contact with microplastics, a factor relevant to chronic low-dose exposure scenarios rather than acute toxicity (Hernandez et al., 2019).

Overall, the bivariate analyses indicate that fecal microplastic abundance is more strongly associated with environmental exposure duration and habitual consumption behaviors, particularly refilled drinking water and teabag use, than with intrinsic demographic characteristics. Nonetheless, the consistently low  $R^2$  values across all variables underscore the multifactorial nature of human microplastic exposure and caution against attributing exposure to a single dominant source based solely on bivariate associations.

### **Multivariate Analysis and Toxicological Interpretation**

Multivariate linear regression confirmed the combined association of length of residence, refilled drinking water consumption, and teabag consumption with fecal microplastic abundance among residents of the Musi River Basin ( $R^2 = 0.312$ ; adjusted  $R^2 = 0.287$ ;  $F = 21.3$ ;  $p < 0.05$ ). Collectively, these variables explained 31.2% of the observed variability, indicating a moderate yet meaningful contribution of environmentally mediated behaviors to human microplastic burden.

Length of residence was significantly and positively associated with fecal microplastic abundance ( $B = 0.186$ ,  $\beta = 0.214$ ,  $p = 0.031$ ), suggesting that prolonged residence in the Musi River Basin is linked to increased microplastic presence in feces. This association is consistent with cumulative environmental exposure rather than biological accumulation per se, as longer residence likely reflects sustained interaction with local water systems and habitual domestic consumption practices. Accordingly, residence duration should be interpreted as an exposure proxy rather than evidence of time-dependent microplastic retention in human tissues.

Refilled drinking water consumption emerged as a significant independent predictor ( $B = 0.241$ ,  $\beta = 0.273$ ,  $p = 0.015$ ), supporting its role as an important environmental exposure pathway. The magnitude of the standardized coefficient indicates that refilled drinking water contributes substantially to fecal microplastic variability after controlling for residence duration and tea consumption. This finding is consistent with the high microplastic concentrations detected in refilled water samples and reinforces concerns regarding filtration efficiency, storage conditions, and quality control in refilled water depots.

Teabag consumption showed the strongest standardized association with fecal microplastic abundance ( $B = 0.278$ ,  $\beta = 0.298$ ,  $p = 0.009$ ). However, this higher  $\beta$ -value should not be interpreted as evidence that teabags represent the dominant source of microplastic mass. Rather, it likely reflects repeated behavioral exposure through frequent brewing events, particularly given that tea preparation in this population uniformly involved refilled drinking water. In this context, teabag consumption functions as an exposure amplifier rather than an independent primary source.

Morphological evidence provides critical support for this interpretation. Black and transparent fragment-type microplastics predominated in both refilled drinking water and fecal samples, whereas microplastics associated with teabags were more commonly fibrous. This morphological concordance suggests that refilled drinking water is the principal contributor of fragment-type particles detected in feces, while teabag consumption primarily increases ingestion frequency rather than fragment load. Consequently, the observed associations reflect overlapping exposure pathways

rather than a statistically tested synergistic interaction, as interaction terms were not included in the regression model.

From a toxicological perspective, the predominance of fragment-type microplastics smaller than 150  $\mu\text{m}$  warrants attention due to their angular morphology, environmental persistence, and potential to induce gastrointestinal irritation during transit (Ragusa et al., 2021). Experimental and mechanistic studies indicate that chronic ingestion of such particles may elicit oxidative stress, inflammatory responses, and disruption of intestinal barrier function (Vethaak & Legler, 2021). Emerging evidence further suggests that sustained microplastic exposure may alter gut microbiota composition and metabolic signaling (D. Zhang et al., 2024); (Lee et al., 2022).

Overall, the multivariate findings indicate that long-term residence and habitual consumption behaviors act as environmentally mediated determinants of fecal microplastic presence in this population. Nevertheless, the moderate explanatory power of the model highlights that a substantial proportion of variability remains unexplained, likely reflecting additional exposure pathways such as airborne microplastics, dietary sources, and occupational factors. Accordingly, these results should be interpreted as evidence of associative exposure patterns rather than causal mechanisms, consistent with the study's cross-sectional observational design.

### **Comparison with Previous Studies**

The findings of this study are consistent with previous investigations reporting microplastic contamination in human feces (Refosco et al., 2025; Schwabl et al., 2019), and drinking water sources (Mason et al., 2020; Yin et al., 2021). In particular, the predominance of fragment-type microplastics observed in fecal samples aligns with reports from freshwater and wastewater systems, supporting the view that inadequately treated or filtered water constitutes a key environmental entry point for human exposure.

However, the mean fecal microplastic abundance observed in this study ( $15.8 \pm 7.6$  particles  $\text{g}^{-1}$ ) was lower than levels reported in several European and East Asian biomonitoring studies (Leslie et al., 2022; Ragusa et al., 2021). This difference should not be interpreted solely as indicative of lower exposure but rather as reflecting contextual variability in analytical methodologies, particle size detection thresholds, population-level consumption behaviors, and regional environmental management practices. Studies employing spectroscopic confirmation and lower particle size cut-offs frequently report higher microplastic counts, which likely contributes to these discrepancies.

Notably, the fragment-dominated microplastic profile identified in this study contrasts with fiber-dominated profiles reported in some bottled and tap water investigations. This divergence suggests that local water treatment infrastructure and distribution systems strongly influence microplastic morphology and abundance. In the context of the Musi River Basin, the predominance of fragments likely reflects secondary microplastics generated through the degradation of plastic components within refilled water treatment, storage, and dispensing systems, rather than fibers originating from textiles.

Compared with studies conducted in high-income countries, where centralized water treatment and stricter quality control measures are more widely implemented, the present findings underscore the continued importance of domestic water sources as determinants of microplastic exposure in urban Indonesian populations. Rather than representing an anomalous pattern, these results highlight how regional environmental conditions and habitual consumption practices shape human microplastic exposure profiles. Accordingly, cross-study comparisons should prioritize differences in exposure pathways and contextual determinants over absolute particle counts alone.

### **Public Health Implications**

These findings indicate that microplastic exposure in urban populations is a multifactorial phenomenon shaped by environmental contamination, consumer behaviors, and prolonged residential exposure. The results highlight an urgent need to strengthen monitoring and quality

assurance in refilled drinking water depots, including the development and enforcement of national standards for microplastic filtration and sanitation. This need aligns with recommendations from the World Health Organization (WHO, 2019), which emphasized the importance of risk-based management approaches for microplastics in drinking water systems.

Public education initiatives should be intensified to improve awareness of microplastic exposure pathways, particularly those associated with plastic-packaged beverages and the repeated use of domestic water containers. At the policy level, integrating environmental toxicology surveillance into existing public health systems could facilitate early detection of exposure trends and inform targeted intervention strategies (Gupta et al., 2023; Sharma & Chatterjee, 2024; UNEP, 2021; Xu et al., 2022).

### **Limitations and Cautions**

Despite several methodological limitations, this study represents a valid and meaningful contribution to understanding human exposure to microplastics in urban environments. The analytical framework, data consistency, and integration of environmental and biological matrices collectively provide credible evidence of potential exposure pathways among residents of the Musi River Basin.

First, polymer composition was not confirmed using spectroscopic techniques such as Fourier-transform infrared (FTIR) or Raman spectroscopy, limiting chemical-level identification. Nonetheless, the morphological characterization applied in this study encompassing particle color, shape, and size distribution follows internationally recognized protocols (F. Li et al., 2024) and offers sufficient reliability for preliminary environmental health assessments, particularly in resource-limited laboratory settings.

Second, although visual microscopy may underestimate microplastics smaller than 50  $\mu\text{m}$ , the consistent detection of particles across refilled drinking water, teabag products, and fecal samples demonstrates analytical robustness and reproducibility. This internal consistency supports the validity of the findings despite the inherent constraints of observational methods (Song et al., 2015).

Third, given the cross-sectional design, causal relationships between specific consumption behaviors and biological accumulation cannot be definitively established. However, the statistically significant correlations and multivariate regression results indicate clear associative patterns between exposure-related behaviors and microplastic presence, in line with previous reports (Catarino et al., 2018).

Fourth, while the sample size ( $n = 97$ ) may not fully capture the heterogeneity of the Palembang population, the inclusion of participants from multiple districts along the Musi River Basin enhances geographic coverage and external validity.

Additionally, other potential exposure pathways such as airborne microplastic inhalation and seafood consumption were not assessed in this analysis. Future studies incorporating these routes are necessary to achieve a more comprehensive evaluation of total human microplastic burden (Catarino et al., 2018). Although strict laboratory contamination controls were implemented, minor airborne contamination cannot be entirely ruled out.

Nevertheless, the study's design, sampling rigor, and triangulation across environmental and biological samples support its overall scientific credibility. The findings provide an important empirical foundation for environmental toxicology research in Indonesia and offer a basis for future mechanistic and longitudinal investigations into human microplastic exposure.

### **Recommendations for Future Research**

Future studies should incorporate polymer-specific analytical confirmation using Fourier-transform infrared (FTIR) or Raman spectroscopy to accurately determine the chemical composition and potential sources of detected microplastics. The adoption of longitudinal or experimental study

designs will be essential to elucidate the dynamics of chronic retention, translocation, and potential biological effects of microplastics within the human body.

Further investigations integrating biomarker-based toxicological assessments such as indicators of oxidative stress, inflammatory responses, and intestinal barrier integrity would provide critical mechanistic insights into the health consequences of microplastic ingestion. Expanding the geographic scope of research to include rural and industrial areas along the Musi River Basin is also recommended to assess spatial variability and identify key environmental determinants of exposure.

In addition, interdisciplinary collaboration among environmental toxicologists, clinical researchers, and public health authorities is needed to establish evidence-based exposure benchmarks and support the development of national guidelines for microplastic control in refilled drinking water systems. Integrating microplastic surveillance into Indonesia's environmental health monitoring framework would strengthen early detection, risk mitigation, and policy responses to emerging microplastic-related health risks.

## CONCLUSION

This study demonstrates that fecal microplastic abundance among residents of the Musi River Basin is associated with environmentally mediated exposure patterns, particularly habitual consumption of refilled drinking water and teabags, as well as longer residence duration. The predominance of black and transparent fragment-type microplastics and their morphological similarity between refilled drinking water and fecal samples indicate consistency in microplastic characteristics across environmental and biological matrices, while teabag consumption appears to function as a behavioral factor that increases ingestion frequency rather than as a dominant contributor to microplastic mass.

From an environmental toxicology perspective, the widespread presence of secondary fragment-type microplastics underscores concerns about repeated gastrointestinal exposure. However, given the cross-sectional observational design, these findings should be interpreted strictly as associative exposure patterns rather than as evidence of causal toxicological effects.

Future research should prioritize polymer-specific identification using FTIR or Raman spectroscopy, followed by longitudinal and biomarker-based studies to more precisely characterize exposure dynamics and potential health implications in human populations.

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**Khairil Anwar** was responsible for data analysis, translation, supervision, and manuscript proofreading. **Miftahurriqiyah** contributed to validation, manuscript review, and editing.

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